Galileo Rubidium Standard and Passive Hydrogen Maser

Current Status and New Development

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Abstract. The pointing accuracy of satellite navigation systems relies to a great extent on the stability of the on-board atomic clocks.

The Passive Hydrogen Maser (PHM) and the Rubidium Atomic Frequency Standard (RAFS) constitute respectively the master and the hot-redundant clock of Galileo Satellite Navigation System. Their development has been continuously supported by ESA.

This article gives a general overview on the RAFS and the PHM current status and the new developments foreseen.

1 Introduction

GALILEO is a joint initiative of the European Commission and the European Space Agency (ESA) for a state-of-the-art global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control. It will probably be inter-operable with GPS and GLONASS, the two other Global Navigation Satellite Systems (GNSS) available today.

The fully deployed Galileo system will consist of 30 satellites (27 operational and 3 active spares), stationed on three circular Medium Earth Orbits (MEO) at an altitude of 23 222 km with an inclination of 56° to the equator.

Atomic clocks represent critical equipment for the satellite navigation system. The Rubidium Atomic Frequency Standard (RAFS) and Passive Hydrogen Maser (PHM) are at present the baseline clock technologies for the Galileo navigation payload. According to the present baseline, every satellite will embark two RAFSs and two PHMs. The adoption of a "dual technology" for the on-board clocks is dictated by the need to insure a sufficient degree of reliability (technology diversity) and to comply with the Galileo lifetime requirement (12 years). Both developments are based on early studies performed at the Observatory of Neuchâtel (ON) from end of 1980s and Temex Neuchâtel Time (TNT) since 1995. These studies have been continuously supported by Switzerland within ESA technological programs especially since the set-up of the European GNSS2 program. Galileo Avionica (GA) started the electronic development of the PHM already in 2000 and EADS Astrium-GmbH (AST-GmbH) jointed the RAFS development activity in 2001.

The activities related to Galileo System Test Bed (GSTB-V2) experimental satellite as well as the implementation of the In Orbit Validation phase are in progress. One experimental satellites was already launched the 28th of December 2005 (GIOVE-A) and the second one (GIOVE-B) will be launched second half 2006. The main objectives of these two satellites are to secure the Galileo frequency fillings, to test some of the critical technologies, such as the atomic clocks, to make experimentation on Galileo signals and to characterise the MEO environment. There are two RAFS on the satellite supplied by Surrey Satellite Technologies Ltd (GIOVE-A) and there will be one PHM and two RAFS on board the satellite supplied by Galileo Industries (GIOVE-B). This article gives a general overview on the space RAFS and the PHM current status and further development foreseen.

2 Current Status of On-Board Clocks

2.1 Current Activities of Rubidium Atomic Frequency Standard

The RAFS clocks on-board of the GIOVE satellites are issued from 8 years of dedicated development activities for navigation application [1] & [2].

Since 2001, a Swiss-German industrial consortium led by TNT with AST-GmbH as the subcontractor for the electronics package is set in place to develop and produce the RAFS clocks. The current model (RAFS2) includes:

- An optimised physics package with low frequency sensitivity to temperature variation (<5E-14/°C) resulting in a better short/mid term stability with a temperature & vacuum environment similar to satellite platform environment.
- A DC/DC converter and the satellite TT&C interface compatible with ESA's last requirements. Figure 4 shows the performances achieved in term of frequency & time stabilities.

Within this configuration RAFS clocks shows capabilities to perform time stability close to 1 ns over 1 day (drift removed) as reported in Fig. 2. It is the type of RAFS on-board of the GIOVE satellites.

In the frame of GSTB-V2, one Qualification Model, one Proto-Flight Model (PFM) and five Flight Model (FM) units have been delivered. The PFM and FM1 are integrated in GIOVE-B and ready for launch. The FM4 and FM5 are integrated in GIOVE-A and in orbit since 28th December 2005. In addition, the FM2 and FM3 are available as FM spare units. Table 1 lists the achieved RAFS performance for GSTB-V2. Fig. 1 shows the measured frequency stability of GSTB-V2 PFM and FM1 to FM5. Fig. 3 shows the RAFS equipment equipped with the thermally regulated base-plate & DC-DC converter.

2.2 Development & Qualification Activities of Passive Hydrogen Maser

The space hydrogen maser will be the master clock on the Galileo navigation payload. The first maser development activity tailored to navigation applications was

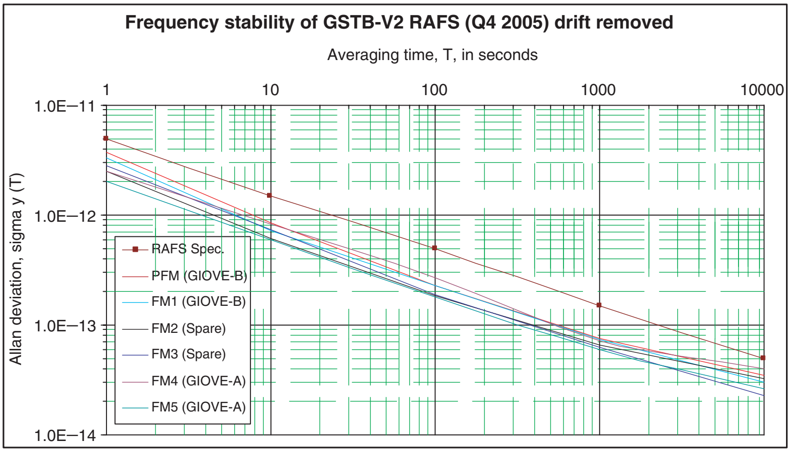

Fig. 1. GSTB-V2 RAFS2 frequency stability.

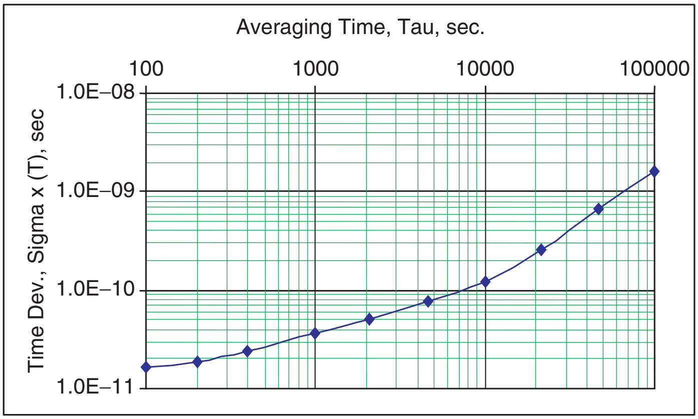

Fig. 2. RAFS stability in the time domain.

Table 1. RAFS for GSTB-V2 performance achieved.

Parameter	Measurement
Frequency stability	< 4* 10^{-14} @ 10,000 sec
Flicker floor	< 3* 10^{-14} (drift removed)
Thermal sensitivity	< 5* 10^{-14} / °C
Magnetic sensitivity	< 1* 10^{-13} / Gauss
Mass and volume	3.3 kg and 2.4 litre

Fig. 3. RAFS equipment in navigation configuration.

kicked off in 1998. It was initiated by the development of an active maser at ON. However, at the Galileo definition phase, it became clear that the accommodation of the active maser on the satellite was too penalizing in term of mass and volume, and the excellent frequency stability performances of the active maser were not required. In 2000 it was re-orientated towards the development of a PHM based on the industrial design and ON heritage on active maser studies.

The development of a prototype was completed at the beginning of 2003 [3], under the lead of ON with Galileo Avionica (GA) subcontractor for the electronics package and TNT supporting the activity in view of the future PHM industrialisation. The instrument has been under continuous test since June 2003 for assessment of long term, reliability and lifetime performances.

The industrialization activity aimed at PHM design consolidation for future flight production was started in January 2003 [4]. The industrial consortium is led by GA designing the electronics package with TNT responsible for the manufacturing of the physical package and the ON supporting the transfer of technology. The overall structure of the instrument was reviewed to increase compactness and to ease the Assembly, Integration and Test (AIT) processes on the satellite by the inclusion of an external vacuum envelope. Main efforts in the industrialization frame focused on the definition of repeatable and reliable manufacturing processes and on the development of more compact electronics. In addition to the PHM Qualification Model, four Models for life demonstration are being manufactured and will be submitted to prolonged testing on ground.

In the frame of GSTB-V2 (now GIOVE-B); one Proto-Flight Model (PFM) was submitted to proto-qualification testing and hence delivered in May 2005. One spare Flight Model (FM1) has been also delivered by Q1 2006. Figures 4 and 5 and Table 2 show the achieved performance of PHM PFM & FM1 for GSTBV2. Better performance has been achieved by improving the magnetron cavity design in the last model (FM1).

Since the beginning of the development, the PHM lifetime was a subject of discussion. The lifetime is being sized to guarantee 12 years of orbit life plus 3 years of ground storage, including the complete AIT program. The operational life is mainly limited by capacities of the hydrogen container (for H_2 supply), bulk getters (for H_2 sorption), ion pump (for pumping ungetterable background gases) and the total dose of ionising radiation. The lifetime capability has been confirmed by detailed analysis and tests of subassemblies (Fig. 6).

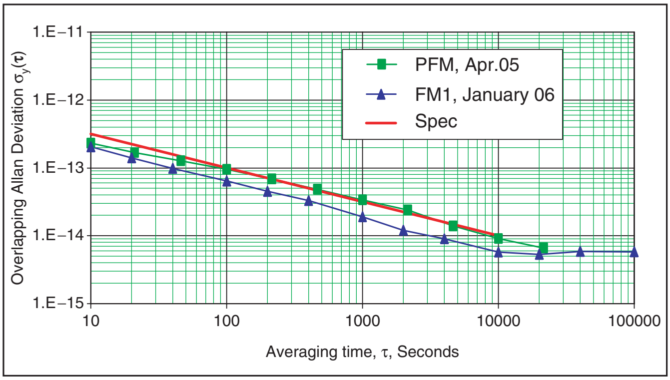

Fig. 4. GSTB-V2 PHM frequency stability.

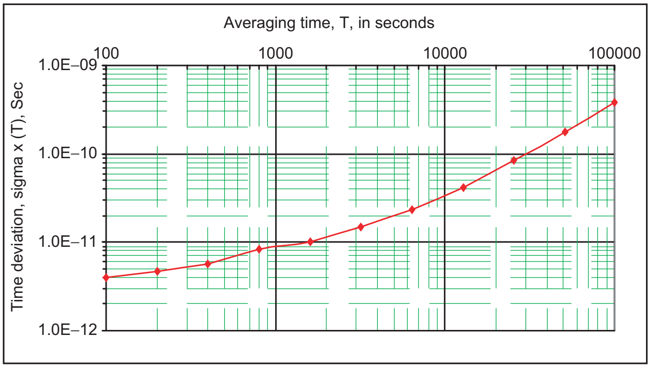

Fig. 5. PHM stability in the time domain.

Table 2. PHM for GSTB-V2 performance achieved.

Parameter	Measurement
Frequency stability	< 1* 10^{-14} @ 10,000 sec
Flicker floor	< 7* 10^{-15}
Thermal sensitivity	< 3* 10^{-14} / °C
Magnetic sensitivity	< 4* 10^{-14} / Gauss
Mass and volume	18 kg and 28 liter

3 Further Development on RAFS and PHM

3.1 Further Development on RAFS

Further investigations to improve the flicker floor are under way. By improving the RF atomic interrogation signal stabilisation circuitry, RAFS has demonstrated stabilities in a range fo 7* 10^{-15} for half of day or longer observation time. A careful

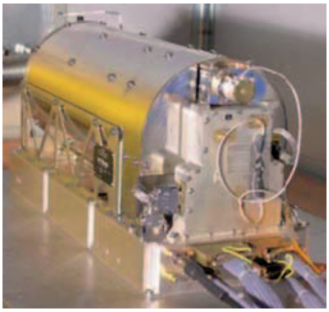

Fig. 6. PHM PFM equipment.

worst case analysis of possibles drifts of parameters has been performed and demonstates the feasibility and possible repeatability of a RAFS having short term stability over one day lower than $1^* 10^{-14}$.

For navigation, the further developments on the RAFS clocks will be concentrated on the improvement of performances. For telecommunication, reduction of the mass, volume and cost of the RAFS are the main drivers of the new development. The goal is to propose a clock with frequency stability of few 10^{-13} within a volume of 1 litre and a mass of 1.5 kg.

3.2 Further Development on PHM

The present PHM instrument is a master clock specifically designed for navigation applications, offering a unique stability performances, requested today by very few other scientific missions, besides navigation.

In order to increase the attractiveness of the PHM and possibly broaden its application field, further developments will be focused on improving its interface characteristics, like mass, size and power consumption, while keeping its very good stability performances and lifetime. In addition, an improvement of thermal sensitivity will be pursued.

4 Conclusions

In total, eight flight clocks were produced for GSTB-V2, which provides the first flight opportunity for Galileo clocks qualification. GIOVE-A with two RAFS onboard is in orbit since 28th December 2005. Both RAFS are fully operational with expected very good frequency stability. The first PHM will be launch very soon on-board of GIOVE-B. With more than 10 years of efforts, two clock technologies for Galileo are qualified. These clocks use reliable and mature technologies leaving room from further improvements in term of mass & performances. Based on this success, new applications could be considered in Europe like for telecommunication or science.

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